ASSESSMENT OF AVAILABLE INFORMATION RELATING TO GEOTHERMAL RESOURCES IN HAWAII

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Division of Water and Land Development

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CONTENTS

Page

INTRODUCTION 1

STUDY OBJECTIVES AND SCOPE 2

GEOTHERMAL ASSESSMENT ADVISORY COMMITTEE 3

GEOTHERMAL EXPLORATION TECHNIQUES 4

Surface Geology 4
Thermal Surveys 4
Groundwater Chemistry, Generally 7
Silica Tests 8
Chloride/Magnesium Ratios 8
Trace Element Chemistry 9
Seismic Surveys 11
Gravity Surveys 12
Magnetic Surveys 13
Electrical Resistivity Surveys 14
Direct Current (DC) or Galvanic Type Resistivity Methods. . 15
Inductive Type Resistivity Methods 17
Self-Potential (SP) Surveys 17
References 19

LITERATURE ABSTRACTS 21

State of Hawaii 21
Hawaii County 23
Maui County 28
Honolulu County 28
Kauai County 29

BIBLIOGRAPHY OF AVAILABLE LITERATURE. 31

Geothermal Resources Generally 31
State of Hawaii 32
Hawaii County 37
Maui County 47
Honolulu County 48
Kauai County 50

GLOSSARY 51

FIGURES

Figure		Page
1A	Lateral view of geothermal reservoir and surrounding rock density structures in the vicinity of HGP-A . . .	5
1B	Lateral view of rock permeability layers in vicinity of HGP-A	5
1C	Generalized depection of a geothermal reservoir	5
2A	Top view of a typical shield volcano, showing the caldera, radiating rift zones, and tangential faults . .	6
2B	Lateral view of Kilauea volcanic complex, showing caldera, central magma chamber, rift zone, and Chain-of-Craters	6
3	Infrared survey on island of Hawaii	8
4	Diagram showing usual Cl/Mg ratios in rain water, perched water, streams, the basal water table, and in sea water	10
5	Normal island basal lens configuration	10
6	Direct, reflected, and refracted waves traveling through two rock strata of difference density	12
7	Electric currents, shown as lines on the earth's cove, are believed capable of producing the earth's magnetic field	14
8	DC electric flow pattern in rock beds of varying resistivities	16
9	The Schlumberger arrangement	16
10	Dipole electrode configuration	16
11	Inductive survey systems	18

INTRODUCTION

The Available Information Assessment is the initial phase in the process of designating geothermal resource subzones in the State of Hawaii as mandated by Act 296, SLH 1983, Relating to Geothermal Energy (Act), and pursuant to the Plan of Study for designating Geothermal Resource Subzones prepared by the Department of Land and Natural Resources in September 1983.

Section 205(c) of the Act provides that the geothermal resource assessment may be based on currently available information. This report is an assessment of information currently available relating to the existence of geothermal resources in Hawaii. This information, along with any other contributions presented to the Department, will be of assistance in determining the location and quality of Hawaii's geothermal resources. A panel of geothermal systems experts has been assembled to advise the Board.

The impact analysis required by section 205(b) of the Act relating to power utilization, geologic hazards, social and environmental impacts, use compatibility, and economics will be forthcoming as outlined in the above mentioned Plan of Study.

This report was prepared by Joseph Kubacki, Energy Specialist, under the general direction of Manabu Tagomori, Chief Water Resources and Flood Control Engineer, Division of Water and Land Development, Department of Land and Natural Resources. The cooperation of Dr. Donald M. Thomas, Geochemist with the Hawaii Institute of Geophysics; the Publications Department at the Hawaii Institute of Geophysics; and the State Department of Planning and Economic Development is acknowledged and greatly appreciated.

STUDY OBJECTIVES AND SCOPE

The basic objective of the Available Information Assessment is to provide a county-by-county compilation of information relevant to determining the existence and location of geothermal resources. The report is divided into five sections:

(1) functions of the Geothermal Assessment Advisory;

(2) a description of geothermal exploration techniques;

(3) abstracts of representative geothermal literature;

(4) a general, statewide, and county-by-county bibliography of geothermal resource literature; and

(5) a glossary of terms used.

The Geothermal Assessment Advisory Committee will assist the Department of Land and Natural Resources in determining the existence and location of geothermal resources. The primer on geothermal exploration techniques may be of assistance while reading the literature presented. Abstracts are provided from a selected cross-section of the bibliography. They should give the reader a quick survey regarding the content of the available information. The bibliography is a general, statewide, and county-by-county compilation of titles which may be obtained from the Department of Land and Natural Resources, Division of Water and Land Development; the Department of Planning and Economic Development, Energy Division; the Hawaii Institute of Geophysics; the U.S. Geological Survey, Geologic Division; and the Hawaii State Library System. Finally, a glossary has been included for the convenience of the reader.

GEOTHERMAL ASSESSMENT ADVISORY COMMITTEE

The Department of Land and Natural Resources has formed a committee of technical experts who are closely associated with the geothermal exploration that has occurred in Hawaii. The Geothermal Assessment Advisory Committee will advise the Department and make appropriate county-by-county recommendations as to the existence and location of geothermal resource areas.

A panel of impact analysts will assist the Department in examining those areas selected as being the most promising geothermal resource locations. The impacts of power utilization, geologic hazards, social and environmental impacts, land use compatibility, economics, and other possible impacts will be fully considered. A recommendation regarding geothermal subzone designations in each county will then be given to the Board for their consideration.

The participation of the committee members, who have volunteered their time and effort, is greatly appreciated.

GEOTHERMAL EXPLORATION TECHNIQUES

The following is a simplified and condensed description of geothermal exploration techniques drawn from references listed at the end of this section. Some applications of these techniques are noted in the abstract section which follows.

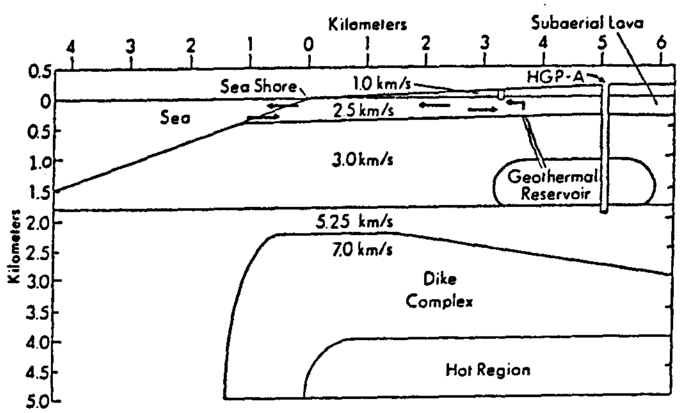
Surface Geology

The easily identified surface structure of island volcanic systems can quickly focus geothermal exploration to a broad area. A geothermal reservoir, the exploration target, usually consists of a permeable rock zone where very hot water is confined by hydrostatic pressure, low-permeability cap rock, or a self-sealing chemical process (see Figure 1). The ultimate heat source for a potential geothermal reservoir is the cooling magma within the caldera or the various volcanic rift zones where extensively fractured rock serves as a conduit for liquid magma (see Figure 2). Broad, gently sloping ridges radiating from the main volcanic caldera are indications of subsurface rift zones originating from the central magma chamber underlying the caldera. Other volcanic surface features include fumaroles (vents for hot volcanic gases), thermal springs, and cinder or spatter cones. To gain a better understanding of subsurface structures; geologic, geochemical, and geophysical techniques are usually integrated when exploring for geothermal reservoirs. While these techniques can infer geothermal resources, the only sure way to confirm the existence and potential production of a reservoir is to drill and test a well.

Thermal Surveys

Well temperature profiles and infrared imagery have been used in Hawaii to directly locate zones of near-surface heat which may be indicative of a nearby deeper geothermal resource. Precise interpretation is difficult as ascending geothermal fluids may take unpredictable paths.

Well temperature data can be obtained by lowering a thermistor into the well hole. The electric resistance of the thermistor varies substantially with changes in ambient temperature allowing for a very accurate temperature reading. Several temperature variation factors must



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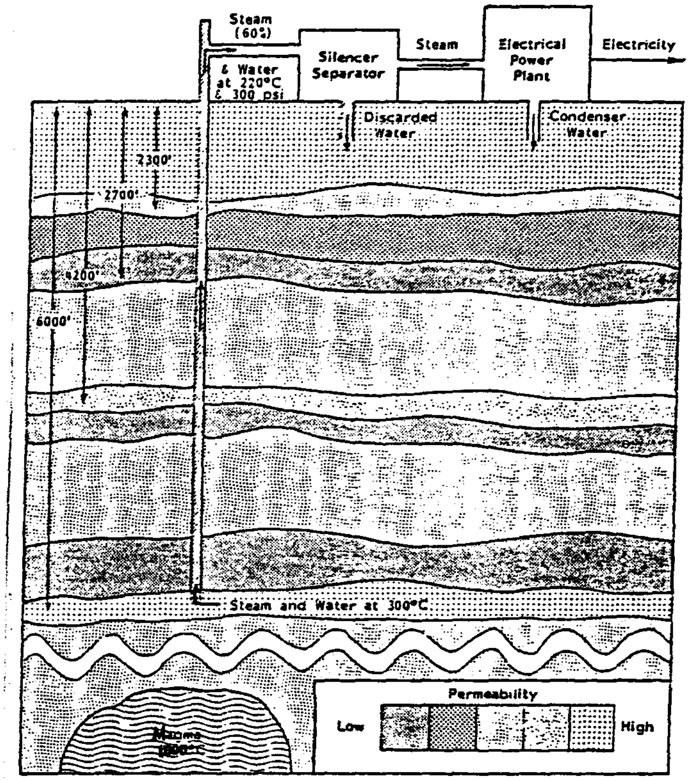

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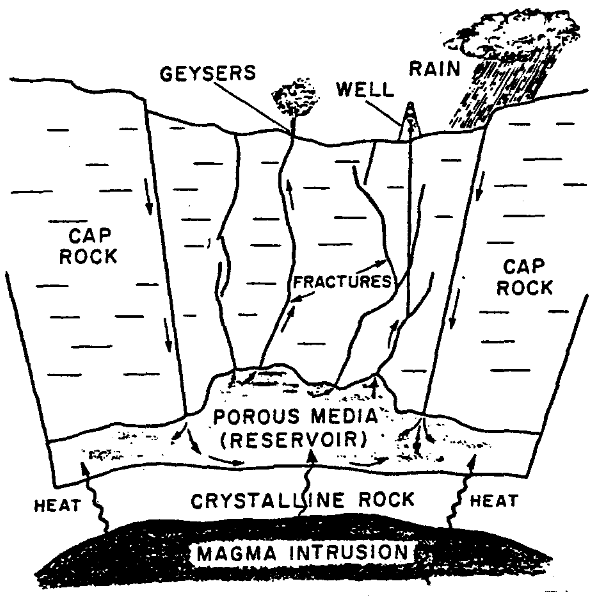
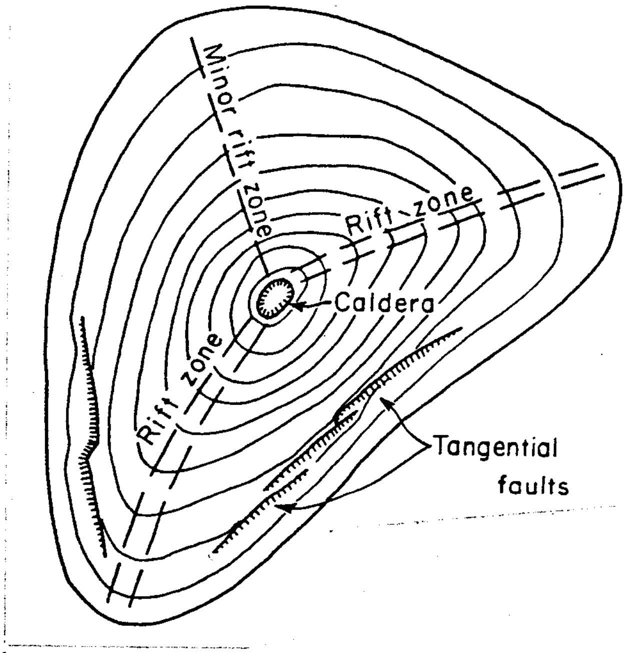


1C

Figure 1A. Lateral view of geothermal reservoir and surrounding rock density structures in the vicinity of HGP-A. Seismic P-wave velocites are shown (Furumoto, 1978).

Figure 1B. Lateral view of rock permeability layers in vicinity of HGP-A (Goodman, et al, 1980).

Figure 1C. Generalized depection of a geothermal reservoir (Keslin, 1980).



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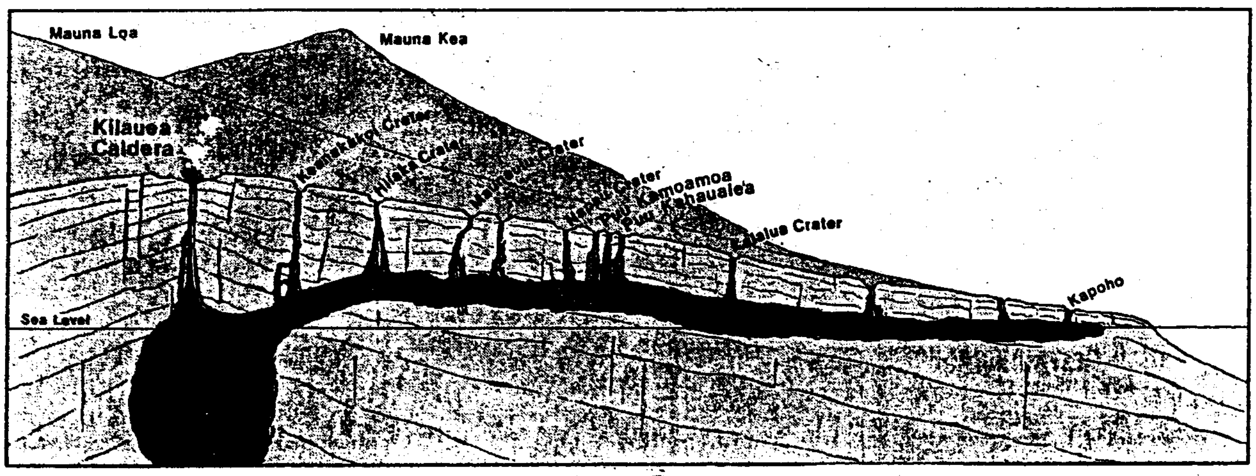


2B

Figure 2A Top view of a typical shield volcano, showing the caldera, radiating rift zones, and tangential faults (Macdonald, et al, 1983).

Figure 2B Lateral view of Kilauea volcanic complex, showing caldera, central magma chamber, rift zone, and Chain-of-Craters (Honolulu Advertiser, Nov. 7, 1983).

be considered when interpreting well temperature data. Infrequently pumped wells are usually selected to insure thermal equilibrium between the water and surrounding rock structure. Consideration must be given to temperature gradients occurring within the well bore which tend to cause convecting cells of water with vertical dimensions several times larger than the hole diameter. Daily and seasonal air temperature variations (quite minimal in Hawaii) can influence water temperatures. Other factors which may also influence groundwater temperature include: the source altitude of recharge fluids in an aquifer, frictional flow, mixing with irrigation water, mixing with saline water, and the targeted factor--geothermal activity. If conditions are right, a well temperature gradient can be established along the length of the well which may be extrapolated to infer temperatures in deeper areas.

Infrared surveys can accurately identify near surface warm water discharges and above ambient ground temperatures. The surveys are usually airborne and conducted at night to provide a greater thermal contrast. The infrared radiation associated with thermal areas can be detected either by special photographic techniques or by using an infrared scanner. The latter yields digital readings which can be reduced to an image with the aid of a computer. Figure 3 is an example of an infrared survey conducted over the island of Hawaii. Infrared surveys can be misinterpreted. Sometimes false positives (anomalous areas of heat) can be inferred where there are unusually high rates of solar insolation or high heat capacities of surface rocks. False negatives can be inferred where cold surface waters overlie deeper thermal fluids.

Groundwater Chemistry, Generally

Certain minerals tend to dissolve out of rocks at high temperatures and other minerals may form when hot water circulates through a geothermal reservoir. As a result, thermal groundwaters can undergo substantial chemical alteration in contrast to nearby cooler groundwaters. Some minerals that respond to warmer groundwater are silica, sodium, potassium, calcium and magnesium. Chemical alteration standards that would indicate a thermally anomalous region are somewhat specific to each site and are quite dependent on rock type and groundwater-route

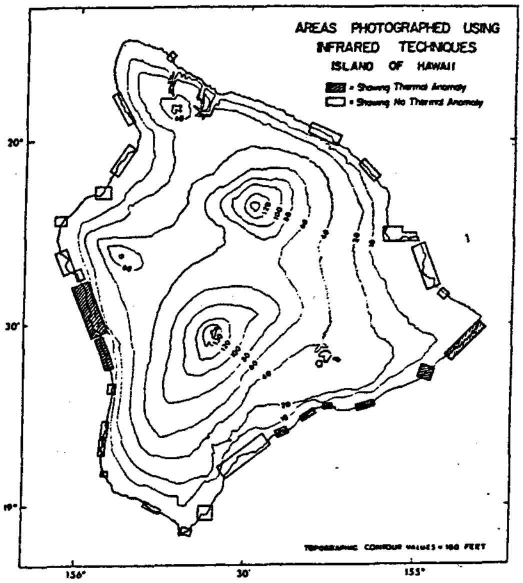


Figure 3. Infrared survey on island of Hawaii (in Thomas, 1979; from Fischer, et al, 1966).

variations in the hydrogeological system. However, some generalizations can be made.

Silica Tests

Two basic screening tests used in locating geothermally altered groundwaters involve temperature and silica concentrations. Concentrations of silica greater than 55 parts per million (ppm) for Oahu (due to human interference with the water cycle) and 30 ppm for other islands are generally considered anomalous. However, because of possible ambiguity in interpreting test data, another test, utilizing the chloride/magnesium (Cl/Mg) ratio in shallow groundwaters has been used to determine geothermal areas with more certainty.

Well test data having unusually high temperature readings or high silica concentrations may indicate a potential geothermal reservoir which can warrant further Cl/Mg ratio tests. Factors controlling the degree of silica concentration include water residence time, rainfall, agricultural activity, and variance in rock composition.

Chloride/Magnesium Ratios

The Cl/Mg ratio in groundwater is a good heat indicator since chloride content is unaffected by heat whereas magnesium is greatly depleted by thermal activity. Heat will usually increase the Cl/Mg ratio.

Depicted in figure 4, as rainwater travels to the basal (fresh) water table the Cl/Mg ratio varies from approximately 7/1 or greater for rainwater (small concentrations of sea salt), to about 2/1 in dike-impounded high-level water and 3/1 in streams (due to Mg dissolving into cool groundwater as it percolates through ground minerals). Sea water has a 15/1 ratio. When fresh water mixes with sea water, the Cl/Mg ratio can vary from 2 to 15 in the transition zone. Fresh water and sea water can be clearly distinguished since salt concentrations are significantly higher in brackish and sea water.

The basal lens aquifer (shown in Figure 5) may be distorted in areas where geothermal heat is transferred to underlying sea water. Normally island basal water floats on top of denser sea water in a lens-shaped configuration. However, if sea water is geothermally heated (e.g. in Kilauea's Lower East Rift Zone) its density is reduced causing it to mix more readily with overlying fresh water. In areas where water is less than 30% sea water, a Cl/Mg ratio greater than 15 may indicate a nearby geothermal reservoir; since heat will cause Mg to precipitate out of the water. If testing results indicate an unusually high Cl/Mg ratio, closer examination may be warranted to determine the cause of the anomaly.

Trace Element Chemistry

Analyses of soil gases for mercury, helium, radon, and other trace elements may indicate leakage of deep geothermal fluids and possibly the presence of hidden fracturing in nearby rock structures. However, soil type must be considered as it can significantly affect the degree of chemical concentration. Anomalous concentrations of these elements are mapped to designate potential geothermal areas.

Radon and helium are gaseous products from the decay of naturally occurring radioactive elements present in all rocks and soils. High concentrations of these elements in soil-gas are usually indicative of subsurface fracturing and may identify areas where geothermal fluids are migrating into shallow aquifers and are releasing dissolved gases.

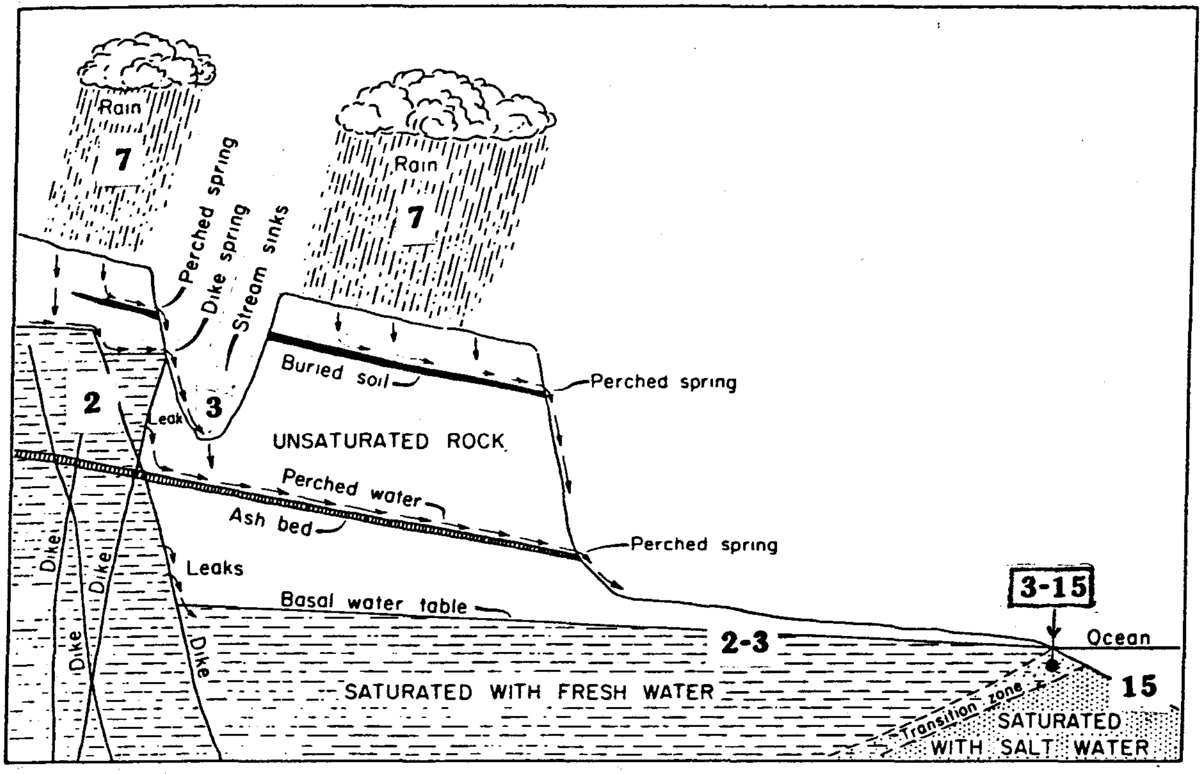


Figure 4. Diagram showing usual Cl/Mg ratios in rain water, perched water, streams, the basal water table, and in sea water (modified from Macdonald, et al, 1983).

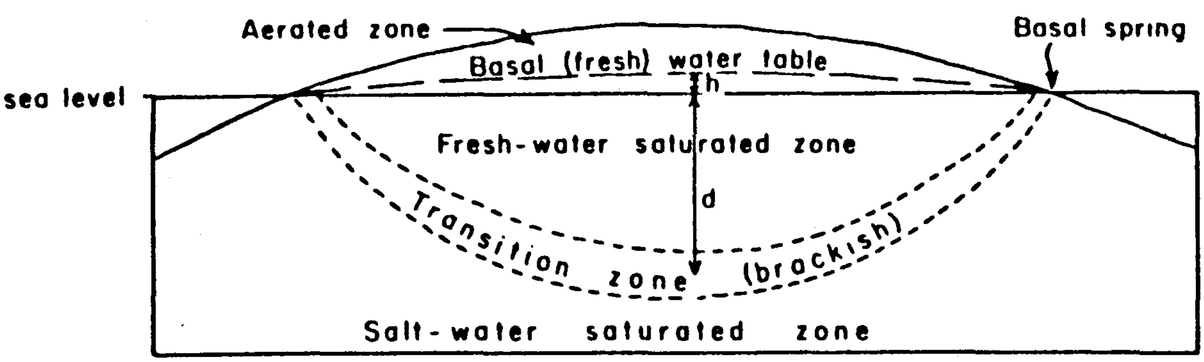


Figure 5. Normal island basal lens configuration (Macdonald, et al, 1983).

Elemental mercury is a slightly volatile element that has a strongly temperature-dependent vapor pressure; and thus tends to migrate away from thermal areas into cooler areas. Mercury concentrations tend to form "halos" around thermal springs or fumaroles.

Seismic Surveys

In Hawaii, geothermal reservoirs are most likely to be associated with rift zones which branch from the central magma chamber of a volcano. Seismic information is useful in determining the location, density, and structure of rift zones and whether they contain still molten or solidified magma. Although these rift zones are the source of geothermal heat, seismic data alone cannot determine the magnitude of heat nor the existence of a useable geothermal reservoir. Other geophysical and geochemical information must be considered to gain a better understanding of potential geothermal reservoirs.

As viscous magma intrudes into the earth's surface it puts stress on surrounding rock formations. As stress increases, the rock becomes strained, may deform, and may eventually fracture releasing heat and elastic energy in the form of shock waves; producing what is generally known as a volcanic earthquake. The exact site of the fracture is the focus or hypocenter. The point directly above on the surface is the epicenter. Most volcanic earthquakes are mild and require sensitive instruments for detection.

There are three basic types of seismic shock waves: P (primary) waves, S (secondary or shear) waves, and surface waves. The P waves are the fastest and move by alternately compressing and pulling the wave medium (e.g. rock) away from the hypocenter. S waves move in a shearing (side to side) motion at right angles to the direction of travel. Liquids (e.g. molten magma) cannot support S waves and can readily be identified by the absence of S waves. S waves travel about one-fourth to one-half the speed of the P wave. This relationship is known as Poisson's ratio. Surface waves, the slowest wave, travel in a circular rippling motion outward from the epicenter. Most seismic analyses utilize P waves which are the easiest to identify. By comparing speed and direction of direct, reflected, and refracted seismic waves (see Figure 6)

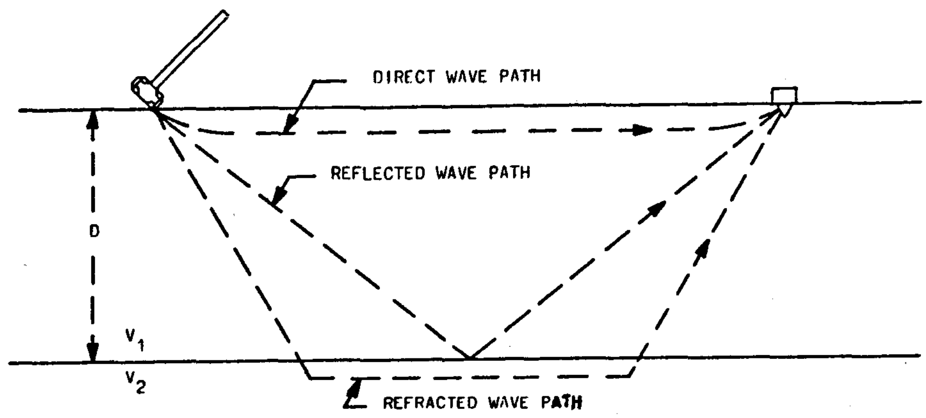


Figure 6. Direct, reflected, and refracted waves traveling through two rock strata of difference density (Mooney, 1973).

the structure and density of various rock layers or volcanic intrusions can be determined. Refraction studies are best suited for determining horizontal structures of dense bodies (e.g. rift zones).

Seismic surveys can be defined as either passive or active. Passive surveys utilize data from natural shock waves produced by the movement of volcanic intrusions to determine the structure of a rift zone and any attendant fracturing. Active surveys utilize shock waves induced by a detonated explosion to determine density and fracturing in underlying rock strata.

The frequency and magnitude of the various seismic waves is measured by a seismograph. It records data on a seismogram which can be interpreted to define rock density and structures usually associated with geothermal resources.

Gravity Surveys

Gravity surveys are of assistance in identifying subsurface rock structures by detecting variations in rock density. These surveys do not measure the absolute gravitational pull of the earth but rather contrast local density variations or anomalies. Data is collected by sensitive gravity instruments in air or, for more localized readings, on land.

In identifying a targeted structure such as a rift zone, raw data must be corrected to account for gravity variations due to latitude, elevation, and terrain. Gravity data alone cannot precisely determine the nature and position of subsurface structures even though density values for most rock types are known (e.g. basalt 2.9 g/cm^3). Data interpretation complications occur because gravity observations detect the sum of the gravitational attractions of all underlying rock layers. Separating the data into component structures is very difficult. An almost infinite number of subsurface structures can combine to result in an identical gravity reading. Other considerations, such as the presence of water or air in porous rock, can also significantly affect density. Therefore, integration of other geologic studies is very helpful in deducing the nature of subsurface structures. Gravity data is quite useful in confirming or narrowing other structural assessments (e.g. seismic, magnetic, and surface geology). In Hawaii, gravity surveys have helped to identify volcanic caulderas and attendant rift zone structures.

Magnetic Surveys

Magnetic surveys are useful in determining the structure and, at times, the temperature of volcanic rift zones and adjacent rocks. Magnetic surveys focus on local variations in magnetic properties of subsurface rock formations.

The ultimate cause of local magnetic anomalies is the planetary magnetic force field produced by the earth. It is believed that liquid iron within the earth's core rotates slowly relative to the solid mantle which surrounds it. This generates electric currents within the core which induce the magnetic field which surrounds the earth (see Figure 7). When a subsurface magma chamber cools (e.g. Kilauea's Lower East Rift Zone), mineral particles of magentite within the magma align in a direction parallel to the lines of force in the earth's magnetic field. When magma cools below the Curie point (about 580°C) the magnetic field generated by the magnetite increases drastically and can be easily detected at the surface.

Magnetic surveys in Hawaii have assumed that the hottest parts (those above the Curie temperature) of a rift zone , i.e. where magentism has not set, are least magnetic and represented by magnetic lows. As cooler (below the Curie temperature) areas of the rift zone are surveyed,

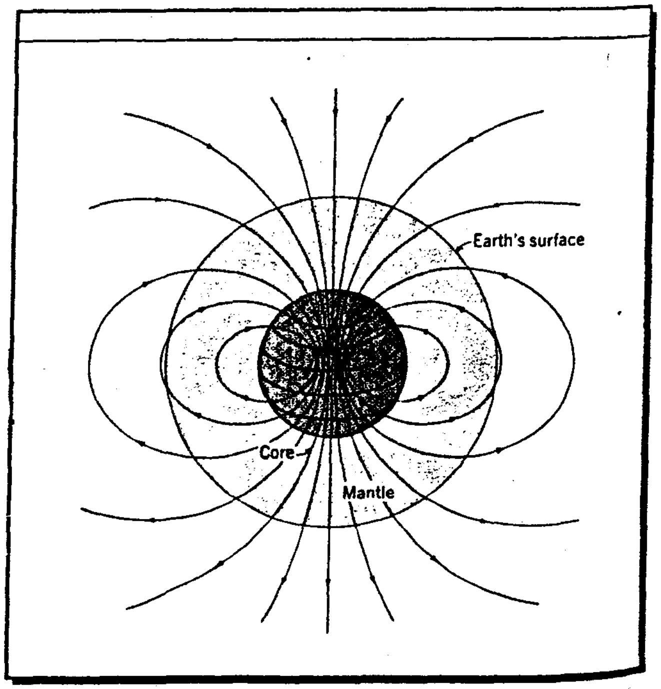


Figure 7. Electric currents, shown as lines on the earth's cove, are believed capable of producing the earth's magnetic field (Strahler, 1981).

magnetic highs are encountered due to the set magnetic alignment of magnitite. In comparison, a gravity survey is likely to register a "high" over the hottest part of the rift zone as density is greatest there.

Airborne magnetic surveys offer extensive and continuous coverage of deeper subsurface features. More costly land surveys are more precise, site specific, and yield information primarily about near surface features. Various corrections (e.g. diurnal variation correction) are made to standardize raw data. Magnetic storms and nearby cultural activities and fixtures should be avoided or taken into account.

Interpretation of magnetic data can be difficult since, as with gravity surveys, the composite effects of all underlying features are measured. Integration of magnetic surveys with other geologic surveys can reduce the potential for ambiguous interpretations.

Electrical Resistivity Surveys

Generally. Electrical resistivity surveys are attractive exploration tools since geothermal reservoir rock can be a relatively good conductor of electricity. By correctly interpreting data from the various rock resistivity surveys certain rock structures and properties can generally be determined at varying depths. Electrical resistivity, or inverse conductivity, will govern the amount of current actually passing through a rock structure. Dry rock is usually highly resistive to current. However the following factors can significantly reduce resistivity:

-- fresh-water saturated rock is significantly less resistive than dry rock;

-- saline-water saturated rock is significantly less resistive than fresh-water sasturated rock;

-- geothermally heated rock stimulates electron flow and reduces resistivity;

-- high rock porosity with water saturation reduces resistivity (deeper, pressurized rock is generally less porous); and

-- geothermal chemical alteration in rock reduces resistivity.

se factors must be carefully considered when data indicate an malously low resistivity.

Both direct current and inductive type resistivity surveys cribed below) have been used in Hawaii to attain high rock structure tion. Due to the inherent sensitivities and normally shallow ration of direct current methods, they are best suited to define ivity within the upper layers of rock structures. Depending on the e of the survey, some resistivity interpretations can be graphed to e a vertical profile or mapped to show horizontal structure.

Current (DC) or Galvanic Type Resistivity Methods

e DC method (also known as the galvanic method) involves electric current into the ground through source electrodes and g the resultant voltage with receiver electrodes at various s (see Figure 8). As the distance between the source and electrodes increases, depth penetration increases and the voltage becomes weaker.

particular type of electrode configuration used in DC surveys is umberger method (see Figure 9). Using this method, the are linearly spaced at progressively greater distances about a ir of stationary, closely spaced, grounded voltage electrodes.

As current electrode spacing increases, depth penetration increases. The wire connecting the outer source electrodes generally varies from 3 to 1000 m. Rock resistivities can be interpreted from known current, measured voltage, and electrode spacing.

The dipole method of electrode configuration is shown in Figure 10. It is based on the same resistivity principles but different mathematical relationships are used to determine resistivity. The wire line connecting the source electrodes generally varies from 1 to 3 km, while the receiver line generally varies from 30 to 3000 m.

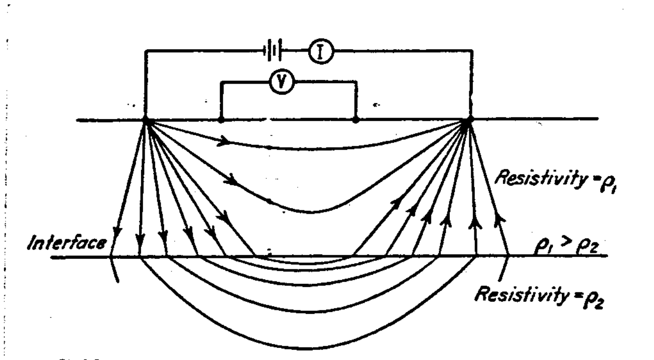


Figure 8.
DC electric flow pattern in rock beds of varying resistivities, where I=source current and V=voltage received (slightly modified from Dobrin, 1976).

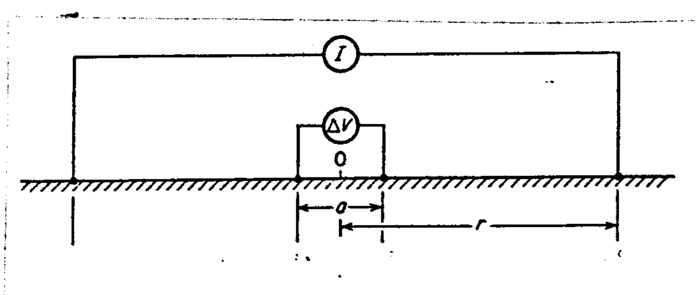


Figure 9.
The Schlumberger arrangement, where distance "a" and "r" may vary but infixed proportions to each other. If current (I) is fixed, measured voltage will vary with electrode spacing and rock resistivity (Dobrin, 1976).

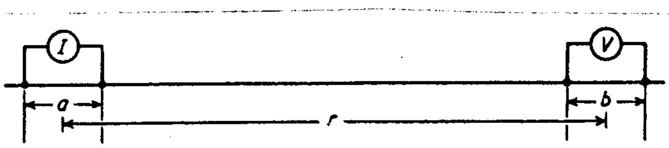


Figure 10.
Dipole electrode configuration (Dobrin, 1976).

Inductive Type Resistivity Methods

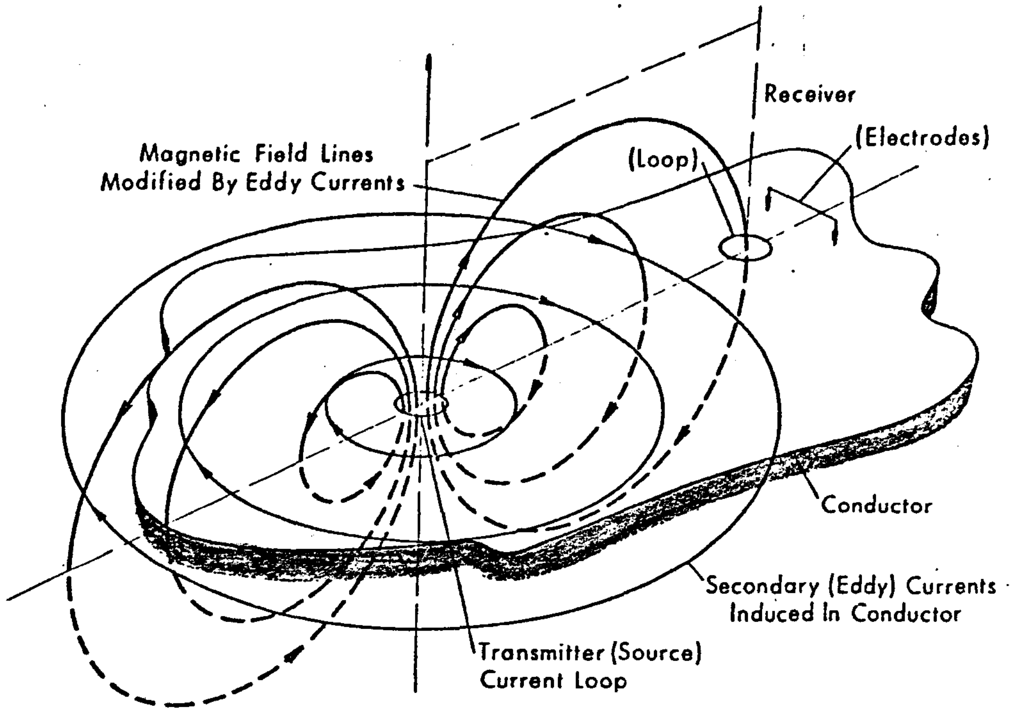
As with DC-galvanic type resistivity surveys, the objective in an inductive survey is to detect buried, conductive (low resistance) rock structures. Referring to Figure 11, the induction method generally involves pulsing a current through the source-transmitter at ground level which generates a primary electromagnetic (EM) field, somewhat similar to a radio wave. The primary EM field induces a secondary current within conductive rock structures below which, in turn, generate their own secondary EM field. This secondary EM field can be detected at ground level by a sensor-receiver. The source-transmitter is usually a large (about 1 km) grounded current line or loop. The secondary EM field is usually measured by a wire line, wire loop, or magnetometer.

Most inductive methods (e.g. the time-domain EM method) determine resistivity by shutting off or pulsing the primary current and monitoring the secondary EM waves for strength and rate of decay. EM waves emanating from rocks with lowest resistivity have greater strength and longer decay times.

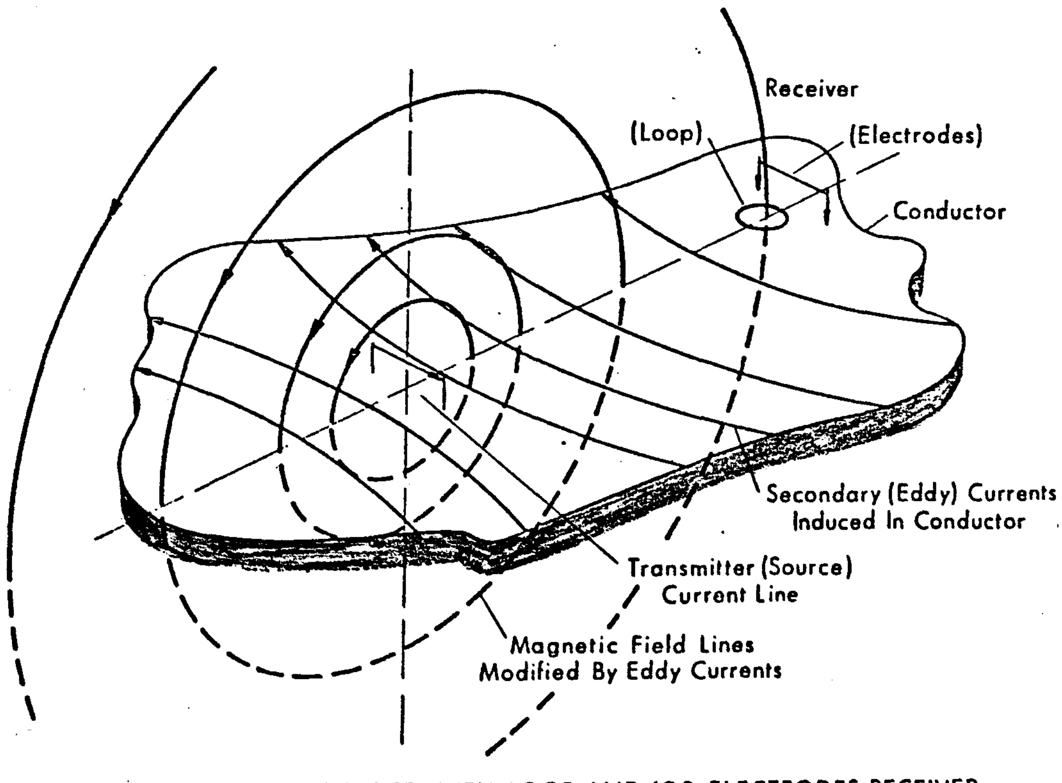
Inductive methods have an advantage over DC type methods in that deeper penetration can be achieved when using comparable amounts of current. Highly resistive rock structures, such as porous, gas-filled surface lava, will quickly dissipate electricity which is directly monitored in DC soundings; whereas the primary and secondary EM waves of an inductive survey have a greater ability to penetrate resistive rock. Depth penetration in an inductive survey increases by lowering the frequency of the primary EM field, with lower resistivity of underlying rock structure, and as the distance between the source and sensor increases.

Self-Potential (SP) Surveys

In Hawaii, SP anomalies have been associated with subsurface thermal anomalies at Kilauea Volcano. The precise reason for the SP anomalies is not well understood. However, it is thought to be associated with an electrokinetic phenomenon. In contrast to most electrical methods, no artificial power source is used. Instead, as thermal convection carries hot brackish fluids upward it causes a displacement of ions along the flow path which can be distinguished from the predominately laterally flowing



LOOP SOURCE WITH LOOP AND/OR ELECTRODES RECEIVER



LINE SOURCE WITH LOOP AND/OR ELECTRODES RECEIVER

Figure 11. Inductive survey systems. Qualitative schematic illustrating the relationships between magnetic fields and induced earth currents for various inductive source-receiver configurations on a uniform, horizontal conducting layer (Klein and Kauahikaua, 1975).

basal (fresh) waters. This can result in a significant electric potential gradient which can be measured by a millivoltmeter. Although SP surveys directly test potential gradients of shallow groundwaters, an SP anomaly may reflect hot water flowing through a permeable vertical fracture connected to a broad heat source at depth. However the precise location of the deep heat source cannot be identified with certainty. Conversely, some geothermal resources, e.g. those not having a fluid discharge to the surface, may not be detected by this method.

The usual SP detection method involves placing electrodes into the ground and "leap-frogging" them over the area to be surveyed. The electrodes are connected by cable to a millivoltmeter which indicates the electric potential gradient. As with other electrical methods, care must be taken to avoid or account for conductive mineral deposits and cultural fixtures (pipes, buildings, powerlines) and activities (irrigation, agricultural chemicals) as these could distort electrical patterns.

Several SP anomalies have been identified in the summit region and along the Lower East Rift Zone of Kilauea Volcano. However, deep exploratory geothermal wells drilled into these anomalies have not always encountered success; e.g. Ashida Well #1, where hot fluids were encountered at 2000 meters, but low permeability prevented flow rates needed for commercial production.

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LITERATURE ABSTRACTS

The following abstracts are representative of the literature compiled in the bibliography. Many of the abstracts listed under "State of Hawaii" contain geothermal information relating to each of the islands specifically. Most abstracts are taken directly from the literature itself; although it may be paraphrased.

State of Hawaii

Cox, M.E., Thomas, D.M., 1979, Chloride/Magnesium Ratio of Shallow Groundwaters as a Regional Geothermal Indicator in Hawaii, Hawaii Institute of Geophysics (HIG) Report No. 79-9.

Because of the complex geological and hydrological conditions and the virtual lack of thermal springs, regional geothermal investigations in Hawaii require the use of techniques substantially different from those conventionally applied in other geothermal environments. The large number of hydrological wells in the state provides an appreciable source of groundwater chemical data. However, largely because of the island environment, interpretation of much of these data as geothermal indicators becomes ambiguous. Initially, SiO_2 concentrations and temperature of groundwaters were used to identify thermally anomalous zones, but on a regional basis it has been found that these criteria are not always successful. As a further criterion for assessment, the Cl/Mg ratio of the groundwater has been used. On a statewide basis, this ratio has been successful in further "screening" the SiO_2-temperature selected sites, and in defining more specific areas which warrant further investigation. Temperature, SiO_2 and Cl/Mg values for nearly 400 groundwater samples are included.

Furumoto, et. al, 1975, Preliminary Studies for Geothermal Exploration in Hawaii, HIG-75-5.

A narrative account of the various stages of the exploration program from 1973 to 1975. The narrative shows how the conclusion was reached to concentrate the exploration program on the east rift of Kilauea volcano as that rift zone showed the most promise of all the volcanic centers and rift zones. The narrative ends at the selection of a drilling site.

The geology and hydrology of the east rift has been summarized to include data existing before the exploration program and some of the early results of the field surveys.

A literature survey of Kilauea volcano attempted to cover the information available on the volcano. The survey includes recent information published by investigators not associated with the Hawaii Institute of Geophysics.

A literature survey of the geothermal potential of the volcanoes on the island of Oahu has already been published elsewhere. A short summary and reference is included in the volume.

Goodman, L.J., Love, R.N., eds., 1980, Geothermal Energy Projects: Planning and Management, Pergamon Press.

This book provides a detailed chronology of the development of geothermal power in Hawaii. A good insight is provided into the factors that influenced project decisions in the areas of exploration, engineering, and environmental control. It describes the roles of particular individuals in the HGP-A project-site selection process.

Macdonald, G.A., Abbott, A.T., Peterson, F.L., 1983, Volcanoes in the Sea; the Geology of Hawaii, University of Hawaii Press.

An excellent sourcebook providing detailed description of the geologic processes occurring in Hawaii. Chapters include: Hawaii Volcanic Activity; Intrusive Bodies; Types of Volcanic Eruptions and Associated Hazards; Groundwater; Rock Deformation, Earthquakes, and Tsunamis; and chapters devoted to the geology of each island.

Naughton, J.J., Thomas, D.M., 1978, Helium in Fumarole and Well Gases as an Index of Long-Term Geothermal Potential, Geoth. Res. Council, Trans. Vol. 2, p. 479.

Fumaroles and degassing vents around Kilauea volcano were used as models of producing geothermal areas. Excess helium has been found in gases from fumaroles characterized by long-term activity, and is absent in gases from short-lived hot spots, from dry vents or fissures formed by recent actrivity, and from old degassed lava lakes. From this it is inferred that the absence of helium in gases from geothermal areas would indicate that they receive heat from a limited magma body, and would be expected to yield extractable heat for only a comparatively short period. The geothermal well at Puna, Hawaii, has given positive helium indications.

Thomas, D.M., et al, 1979, Potential Geothermal Resources in Hawaii: A Preliminary Regional Survey, HIG-79-4.

A regional geothermal resource assessment has been conducted for the major islands in the Hawaiian chain. The assessment was made through the compilation and evaluation of the readily accessible geological, geochemical, and geophysical data for the Hawaiian Archipelago that have been acquired during the last two decades.

The geologic criteria used in the identification of possible geothermal reservoirs were age and location of most recent volcanism on the island and the geologic structure of each island. The geochemical anomalies used as traces for geothermally altered groundwater were elevated silica concentrations and elevated chloride/magnesium ion ratios. Geophysical data used to identify subsurface structure with possible geothermal potential were aeromagnetic anomalies, gravity anomalies, and higher-than-normal well and basal spring discharge temperatrues.

Geophysical and geochemical anomalies that may be the result of subsurface thermal effects have been identified on the islands of Hawaii, Maui, Molokai, and Oahu.

D.M., et al, 1980, Preliminary Geothermal Assessment Surveys for the State of Hawaii, Geoth. Res. Council, Trans. Vol. 4, p. 185-8.

The Geothermal Resource Assessment Program of the Hawaii Institute of Geophysics has conducted a series of geochemical and geophysical surveys in ten separate locations within the State of Hawaii in an effort to identify and assess potential geothermal areas throughout the State. The techniques applied include groundwater chemistry and temperatures, soil mercury surveys, ground radon emanometry, time-domain electromagnetic surveys and Schlumberger resistivity soundings. Although geochemical and geophysical anomalies were identified in nearly all the survey sites, those areas which show most promise, based on presently available data, for a geothermal resource are as follows: Puna, Kailua Kona, and Kawaihae on the island of Hawaii; Haiku-Paia and Olowalu-Ukumehame canyons on Maui; and Lualualei Valley on Oahu. Further surveys are planned for most of thsese areas in order to further define the nature of the thermal resources present.

D.M., et al, 1980, Direct Heat Resource Assessment: Final Report, DOE/ET/27023-4, HIG.

The exploration techniques applied to the islands of Hawaii, Maui, and Oahu include (1) groundwater chemistry, (2) mercury-radon surveys, (3) isotopic composition of groundwaters, (4) time domain electromagnetics, and (5) Schlumberger resistivity surveys. The results of these surveys can be classified as follows: (1) Hawaii: Kailua-Kona, strong geochemical anomalies; Kawaihae, strong geophysical anomalies, moderate to strong geochemical anomalies; Hualalai northwest rift, weak geochemical and moderate geophysical anomalies; South Point, moderate to weak geophysical anomalies; Hualalai southeast rift, weak geophysical anomalies; Keaau, weak geophysical and geochemical anomalies; (2) Maui: Haiku-Paia, strong geochemical anomalies; Olowalu-Ukamehame canyons, moderate to strong geochemical and geophysical anomalies; Lahaina, weak geochemical and geophysical anomalies; (3) Oahu: Lualualei, moderate to strong geochemical and geophysical anomalies; Waimanalo-Maunawili, insufficient data.

Fan, P.F., 1976, Hydrology and Chemistry of Groundwater Puna, Hawaii, Groundwater, Vol. 14, p. 328-338.

Presented is an analysis of the hydrology and chemistry of the ground water of the Puna District, Hawaii, based on data from 16 drilled wells, ten test wells, two shafts and four exploratory thermal wells. Ground water occurs as (1) perched water located north of Mountain View; (2) dike water located along the east rift zone of Kilauea; and (3) basal water occurring throughout most of the district, except where dike water is present. The east rift zone serves as a barrier to ground-water movement, as demonstrated by the difference in basal water-table levels on the two sides of the rift zone. Salinity and temperature of the bgasal ground water varies greatly north and south of the rift zone due to differences in precipitation, sea-water instrusion, volcanic activity, flow rates, permeability, and discharge.

Basal ground-water type is predominantly sodium chloride. Water samples taken from thermal test well No. 3 showed dissolved silica values two to three times higher than the 49 mg/l average for the rest of the island. Hydrologic and geologic conditions in and around Kilauea's east rift zone support the possibility of accumulations of superheated ground water. The mixing of waters of difference composition at depth proved to be the most difficult problem encountered in estimating deep ground-water temperatures.

Epp, D., Halunen, A.J., 1979, Temperature Profiles in Wells on the Island of Hawaii, HIG-79-7.

Tempeature versus depth is reported for 21 wells on the island of Hawaii. The highest temperatures were measured in wells on Kilauea's east rift zone in the Puna area. Temperatures decrease rapidly north and south of the rift zone. Above-average temperatures were observed in two wells in the South Kohala area.

Furumoto, A.S., 1976, A Coordinated Exploration Program for Geothermal Sources on the Island of Hawaii, HIG contr. 673.

Staff members of the Hawaii Institute of Geophysics carried out an exploration program for geothermal sources on the island of Hawaii by using all relevant geophysical and geochemical methods. Infrared scanning surveys by aircraft followed by reconnaissance-type electrical surveys and ground-noise surveys narrowed down the promising area to the east rift of Kilauea.

The surveys carried out over the east rift included magnetic, gravity, and electrical surveys by various methods; microearthquake surveillance; temperature profiling of wells; and checmial analysis of water samples. Aeromagnetic, regional gravity, and crustal seismic refraction data were available in the published literature.

A model of the thermal structure of the east rift was put together to account for the data. The dike complex through which magma from the central vent of Kilauea travels laterally occupies a zone 3 km wide extending from a depth of 1 to 5 km. On the south side of the dike complex, there may be a self-sealing geothermal reservoir where ground water heated by the dike complex is trapped. Not all of the dike complex is hot; hot sections seem to occur in patches.

moto, A.S., 1978, Nature of the Magma Conduit Under the East Rift Zone of Kilauea Volcano, Hawaii, Bull. Volcanol., Vol. 41-4.

From a combination of results of gravity, magnetic and seismic refraction surveys, the dike complex under the east rift zone of Kilauea Volcano in Hawaii was found to extend for 110 km from the summit area of the volcano to a point 60 km at sea beyond the eastern tip of the island. Near the summit the complex is 20 km wide, and at about 40 km distance from thje summit, the complex narrows to 12 km wide. The main body of the dike complex is 2.3 km deep, but some parts are as shallow as 1 km.

From extrapolation of temperature data of a deep well and from analysis of magnetic data, it was inferred that temperature of the dike complex is above the Curie point of 540°C. The interna. part of the complex can approach the melting point of 1060°C.

The Dike complex was formed by numerous excursions of magma from the holding reservoir under the volcano summit. The theory of forceful intrusion of magma into rift zones accounts for the magma excursions and migration of the passageways.

Gravity and seismic velocity data indicate that density of the material left in the dike complex is 3.1 g/cm^3. In the light of recent density determinations of Hawaiian rocks under high pressure and temperature, it is concluded that during Hawaiian volcanic activity, less dense components of the parent magma erupt through surface vents while the more dense components remain trapped below. Samples of the dense material from the dike complex are required before we can have a complete picture of the parent magma of Hawaiian volcanoes.

The dike complex is the source of thermal energy for a commercial quality geothermal reservoir that was found by drilling.

S., 1978, The Relationship of a Geothermal Reservoir to the Geological Structure of the East Rift of Kilauea Volcano, Hawaii, Geoth. Res. Council, Trans., Vol. 2, p. 199.

The geological structure of the east rift of Kilauea, obtained by geophysical surveys, is provided. The source of energy was a not, broad dike complex at a depth of 2.3 km. The geothermal reservoir is located in a rock layer with fractures caused by tensional stresses. The reservoir was capped by a self-sealing process due to filling of fractures by secondary minerals.

et al, 1977, Geoelectric Studies on the East Rift, Kilauea Volcano, Hawaii Island, HIG-77-15.

This publication contains four individual reports using geoelectric methods to survey the geothermal potential of the island of Hawaii:

(1) Electrical Resistivity and Time-Domain Electromagnetic Surveys of Puna and Kau Districts, Keller, et al.

It was found that the flanks of Mauna Loa are underlain by rocks of high resistivity, and that such rocks probably extend into the Puna area along the projection of an ancient rift zone. The high resistivities probably represent the presence of dense, cool, dike complexes, so that this portion of the area is unlikely to have much prospect for geothermal development. Resistivity values are compatible with the presence of thermal waters with temperatures above 180°C, probably extending to a depth of 2 km below sea level. Measurements taken around the summit area of Kilauea confirm the existence of a brackish-water geothermal system along the south side of Kilauea caldera, in the vicinity of the Kilauea Geothermal Test Well.

(2) Electromagnetic Sounding Measurements, Kauahikaua and Klein.

Variable frequency inductive sounding measurements taken with the horizontal, coplanar two-loop configuration, as well as Schlumberger direct current sounding measurements, were made on the lower east rift of Kilauea volcano, Hawaii. The saturated substratum shows resistivities of 100 to 600 ohm-m where fresh water is present and resistivities less than 6 ohm-m where water is more saline.

(3) Interpretation of Electromagnetic Transient Soundings Made on the East Rift of Kilauea, Kauahikaua and Klein.

Their data indicates a low resistivity zone in the HGP-A area and the Honuaula crater area. Authors conclude that the low resistivities at depths of 1 km result from water temperatures of 200-250°C.

(4) Self-Potential Studies in East Puna, Hawaii, Zablocki.

Self-potential (SP) studies made in the area of Kilauea volcano's lower east rift zone (East Puna) delineated four positive-potential anomalies that are most likely related to magma or hot intrusions at depth. Previous and concurrent SP studies in Kilauea's summit area showed that similar types of anomalies can be related unambiguously to such localizations of heat. Three of the anomalies mapped in East Puna are elongate parallel to the rift zone. SP features in this area reflect permeable, vertical fractures that have hot-water continuity with a relatively broad heat source at depth.

Ross, H.P., 1982, <u>A Review of Public Geophysical Data, Kilauea-East Rift Area, Hawaii</u>, prepared for Thermal Power Co., Honolulu.

Data is represented on eleven large maps which accompany the report. Maps include: geology and thermal wells, gravity, magnetics, electrical resistivity surveys, seismic data, self potential, and an integrated data summary. The author suggests that the rift zone roughly coincides with gravity data but is not sharply defined by the data. A strong magnetic source corresponds to the southern edge of the rift zone between Chain of Craters and Iilewa Crater. Limited well temperature data suggests that heat sources are limited to the rift zone itself. Low apparent resistivities occur at depth throughout much of the rift zone due to salt water, porosity, and in some areas high temperature. The electrical resistivity data base, although extensive, is not of adequate detail to delineate geothermal reservoir(s).

The author states that the HGP-A area appears to be the most promising reservoir area but another area 7 km southwest of HGP-A also seems promising. Other reservoirs may be present but not clearly indicated because of the irregular distribution of data. The author recommends a low-level aeromagnetic survey receive high priority in further exploration. Present estimates of the lateral extent of the reservoir, based on microearthquake data, is premature and subject to considerable error.

Suyenaga, W., et al, 1978, Seismic Studies on Kilauea Volcano, Hawaii Island, HIG-78-8.

This volume contains reports on seismological studies done in conjunction with other geophysical and geochemical studies of the Hawaii Geothermal Project. The studies were conducted on the easternmost portion of the East Rift Zone of Kilauea Volcano, near the eventual site of the initial well, HGP-A, drilled by the Hawaii Geothermal Project. The microearthquake survey by Suyenaga and Furumoto found, among other patterns of seismicity, a small cluster of events at 1 to 3 km depth in the immediate vicinity of HGP-A. Another microearthquake survey conducted by Mattice and Furumoto over a high electrical conductivity anomaly located west of HGP-A found it to be probably more seismically active than the area around the well site. Norris and Furumoto contoured noise levels but found no local amplification at any frequency associated with the geothermal reservoir. However, noise may be associated with magmatic activity. The crustal structure of the area was studied with two sets of seismic refraction profiles reported by Suyenaga and by Broyles. The surface layer has a low but highly variable velocity (0.8 to 1.6 km/sec) and consists of interlayered aa and pahoehoe flows with large voids. A jump in velocity to 2.5 to 3.0 km/sec occurs near sea level and is attributed to saturation of water. A layer of velocity about 5.0 km/sec lies between the 3.0 km/sec and a 7.0 km/sec layer. The latter is interpreted as the dike complex and locally is found as shallow as 2 to 2.5 km. Furumoto combines microearthquake, source mechanism, gravity, and thermal data into an interpretation of the process of geothermal reservoir formation in the East Rift Zone (see Figure ___ on page ___ of this report).

Thomas, D.M., 1982, A Geochemical Case History of HGP-A Well, 1976-1982, Proc. Pac. Geoth. Conf., p. 273-8.

The Hawaii Geothermal Project Well-A, located on the island of Hawaii, was completed in 1976 to a depth of 1966 meters. The bottomhole temperature, under shut-in conditions, is 360°C and at full discharge is capable of producing about 45,500 kg/hr of a mixed fluid composed of 48% steam and 52% liquid. The major element chemistry of the fluids suggests that recharge to the reservoir is largely fresh meteoric water with no more than 10% to 15% of the recharge being from sea water. Extensive water-rock equilibration has occurred; however neither Na-K-Ca nor silica geothermometry calculations have been able to yield reasonable reservoir temperatures. Isotopic data suggest that the circulation rate and residence times of fluids in the reservoir are on the order of a few thousand years. Helium isotopic data also indicate that the heat source for this reservoir is very young or very large.

Thomas D.M., 1980, Water and Gas Chemistry from HGP-A Geothermal Well, Geoth. Res. Council, Trans. Vol. 4, p. 181.

During January 1980, a two-week production test was conducted on the goethermal well HGP-A. Brine chemistry indicates that approximately six percent of the well fluids are presently derived from seawater and that this fraction will probably increase during continued production. Reservoir production is indicated to be from two chemically distinct aquifers: One having relatively high salinity and low production and the other having lower salinity and producing the bulk of the discharge.

Maui County

Cox, M.E., Cuff, K.E., 1980, Rn and Hg Surveys: Geothermal Exploration in N.E. Maui, Hawaii, Geoth. Res. Council, Trans. Vol. 4, p. 451.

Regional assessment for geothermal potential in Hawaii indicated thermal alteration of shallow groundwater in northeast Maui. Studies within the area, the lower north rift of Haleakala volcano, include the measurement of ground Rn emanation, soil Hg concentration and soil pH. Anomalous results from these geochemical techniques are reasonably coincident, and are located over the western boundary of the rift structure. These studies suggest anomalous subsurface temperatures associated with the rift and consequent enhancement of ground gas outgassing. Further surveys, both geochemical and geophysical, are currently being carried out to confirm these conclusions.

Honolulu County

Cox, M.E., et al, 1982, A Preliminary Geothermal Evaluation of the Mokapu Peninsula on the Island of Oahu, Hawaii, HIG-82-2.

In the context of the geothermal potential of the Mokapu Peninsula, the results of the present survey can be summarized as follows:

1) The geological data suggest that the post-erosional volcanism associated with the Mokapu Peninsula was of such a short duration and is of such great age that it is unlikely that significant remnant heat would be found beneath these structures. Although remnant heat may still be present within the magma chamber of Koolau volcano, no geologic evidence has been found to substantiate its occurrence.

2) The geochemical data indicate that one area within the peninsula may be slightly anomalous; however, no firm conclusions can be drawn concerning its relationship to a potential heat source. Limited groundwater geochemical data for the peninsula do not suggest the presence of thermally altered groundwater, although some indication of groundwater anomalies have been identified several kilometers to the south of Mokapu Peninsula.

3) The results of geophysical surveys suggest that the peninsula is underlain by seawater-saturated clays at local ambient temperatures.

Therefore, the probability for the occurrence of an exploitable high-temperature resource beneath the Mokapu Peninsula is extremely low, and the probability for a low-temperature resource at economically viable depths is also very low.

Cox, M.E., et al, 1979, Investigation of Geothermal Potential in the Waianae Caldera Area, Western Oahu, Hawaii, HIG-79-8.

Geologic mapping identifies several caldera and rift zone structures in the Lualualei Valley and provides a tentative outline of their boundaries. Clay mineralogy studies indicate that minor geothermal alteration of near-surface rocks has occurred at some period in the history of the area. Schlumberger resistivity soundings indicate the presence of a low resistivity layer beneath the valley floor, which has been tentatively attributed to warm water-saturated basalt. Soil and groundwater chemistry studies outline several geochemical anomalies around the perimeter and within the inferred caldera boundaries. The observed anomalies strongly suggest a subsurface heat source. Recommendations for further exploratory work to confirm the presence of a geothermal reservoir include more intensive surveys in a few selected areas of the valley as well as the drilling of at least three shallow (1000-m) holes for subsurface geochemical, geological and geophysical studies.

Kauai County

Krivoy, K.L., et al, 1965, A Reconnaissance Gravity Survey of the Island of Kauai, Hawaii, Pac. Sci., Vol. 21, No. 3.

A large gravity anomaly on Kauai, similar to anomalies found at most of the other major volcanoes of the Hawaiian Islands, lies about 10 miles east of the caldera indicated by geologic mapping. Another gravity high suggests a second center of volcanism just west of the island.

Average gravity values on Kauai are higher than on other Hawaiian islands, indicating either that the crust beneath Kauai is 1-2 km thinner than it is beneath the eastern part of the Hawaiian Chain, or that the zone of increased density in the dike complex lies closer to the surface at Kauai than do similar cores within other islands of the chain.

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Anomaly - A deviation from uniformity capable of being distinguished by geochemical or geophysical measurement.

Aquifer - A water-bearing layer of porous rock, sand, or gravel.

Basal groundwater or lens - In Hawaii, fresh water percolates quickly downward through the permeable rock into a zone of complete saturation forming a basal lens. This lens floats on top of denser sea water underlying the islands. (See Figure 5, page 10)

Basalt - A fine-grained igneous rock of recent volcanic origin dominated by dark-colored minerals, usually magnetic.

Bipole - A dual electrode arrangement in which the electrodes are an appreciable distance apart.

Caldera - A particular type of crater, found at the summit of volcanoes. It is elevated, usually bounded by steep cliffs, and has a diameter many times greater than the volcanic vent or opening. Compare with crater.

Cap rock - A relatively dense layer of rock that prevents the circulation of heat or fluids. Geothermal reservoirs are confined by either a cap rock, hydrostatic pressure (pressure exerted by overlying water), or by a self-sealing chemical process.

Cinder cone - A conical elevation formed by the accumulation of volcanic ash or clinkerlike material around a vent. These cones can be a surface manifestation of underlying rift zone. The cinders, originating from volcanic fountains, have solidified in air; whereas, lava that is still partly liquid when it hits the ground is termed spatter. These cones are along Kilauea's Chain-of-Craters.

Conduction - The transference of heat through a medium or body driven by a temperature difference and involving no motion of the medium, e.g. heat transfer from magmatic heat source to geothermal fluids. Compare with convection.

Convection - Transfer of heat from one place to another by actual motion of the heated gas or fluid, e.g. geothermal reservoir fluids. Compare with conduction.

Crater - Bowl-shaped or funnel-shaped depression directly above a volcanic vent.May be above a volcanic rift zone.

Curie point - The temperature at which a material loses its ability to retain magnetism; in rocks usually about 600°C. Useful in determining subsurface temperatures by magnetic surveying.

Dike - A narrow igneous intrusion that cuts across the structure of adjacent rock beds. Sometimes it may act to confine water within a rock strata.

Dipole - A pair of oppositely charged electrodes that ideally are infinitesimally close together.

Diurnal variation - Daily fluctuations of the earth's geomagnetic field, related principally to the tidal motion of the ionosphere. The ionosphere, in the upper atmosphere, includes several layers of ionized gas which bend certain electromagnetic waves back towards earth.

Electric potential - Electrical voltage with respect to a reference point.

Electromagnetic prospecting - A geophysical method that uses the generation of electromagnetic waves at the earth's surface to penetrate the earth and contact conducting formations or ore bodies. Currents are induced in the conductors which provide the source of new waves that radiate from the conductors and are detected by instruments at the surface. A type of electrical resistivity survey.

Electrical resistivity survey - Survey based on conductive properties of rock to determine the nature and location of anomalous rock structures.

Geothermal reservoir - Commercially exploitable areas of subsurface hot water contained in permeable rock and confined by nonpermeable rock or hydrostatic pressure.

Geophysical prospecting - Determining rock structures by measuring magnetic fields, gravity, electrical properties, or seismic waves.

Inductance - The capability of an electric circuit to induce an electromagnetic field about the circuit.

Lava - Fluid rock that issues from a volcano or a fissure in the earth's surface; also the same material solidified by cooling.

Magma - Molten rock material within the earth, the cooling of which produces an igneous rock (e.g. basalt).

Magnitite - A magnetic iron mineral, traces of which are found in many rocks. See Curie point.

Overburden - Material that overlies a deposit of useful minerals.

Percolate - To pass or filter through; as water percolates through soil and permeable rock.

Permeability - A measure of the ease with which liquids and gases can pass through a rock.

Porosity - The proportion of empty space within a rock; may be stated as a percent.

Rift zone - A zone of extensively fractured rock, radiating from the central magma chamber of a volcano, which serves as a conduit for magma (see Figure 2, page 6).

Seismic - Pertaining to an earthquake or earth vibration, including those that are artifically produced. Can be interpreted to determine rock structures.

Spatter cones - See cinder cones.

Thermal gradient - The rate of increase or decrease in temperture with distance in a specified direction.